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TECHNICAL NOTE 2424

FLIGHT INVESTIGATION OF THE EFFECT OF TRANSIENT WING RESPONSE ON WING STRAINS OF A TWIN-ENGINE TRANSPORT AIRPLANE IN ROUGH AIR

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SUMMARY

A flight investigation was made on a twin-engine transport airplane to determine the strains associated with the dynamic behavior of the wing during flights through rough air. Flights were made in clear-air turbulence for different wing fuel loads and for two speed conditions at altitudes between 3,000 and 4,000 feet. Slow pull-ups were made in smooth air to obtain data for a reference quasi-static condition. Simultaneous measurements were made of nodal-point acceleration and of wing strains at a number of spanwise stations.

The bending strains per unit normal acceleration in gusts were approximately 20 percent higher than those in slow pull-ups for all measuring positions and flight conditions of the tests. The dynamic component of the wing bending strains appeared to be due primarily to excitation of the fundamental wing bending mode. The data on spar web strain exhibited a rather large amount of scatter, and the estimated web strain amplifications for gusts relative to pull-up conditions varied considerably with measuring station.

INTRODUCTION

Although the treatment of gust loads on airplanes has usually been made on the basis that the airplane is rigid, the dynamic response of airplane wings due to gusts has been of concern since early gust-load studies (see reference 1). Higher speeds, thinner wings, larger proportions of the total mass carried in the wings, and so forth have led to increased concern as to the effects of wing flexibility for postwar airplanes in flights through gusts. Although a number of investigations of the structural dynamic response have been made (see list of references in reference 2), almost all the investigations to date have been either in regard to the development of analytical methods for calculating structural responses of airplanes in gusts or in making trend studies. In order to evaluate these various methods of predicting structural dynamic response and to establish the magnitude of structural dynamic-response effects appropriate to present-day airplanes in actual operations, rough-air flight data are needed.

In order to help assess the effect of wing flexibility on accelerations and wing strains, a flight investigation was made on a modern twin-engine transport airplane. Acceleration and strain measurements were made at a number of spanwise stations during flights through clear-air turbulence. Similar measurements were made during slow pull-ups in smooth air to obtain data for a quasi-static reference condition. The part of the investigation dealing with the effects of structural response on acceleration measurements is reported in reference 3. The present paper contains results pertinent to the strain measurements. Amplification factors of strain for gust conditions relative to a quasi-static reference condition are given. These amplification factors are found by comparing the strains that are obtained per unit normal acceleration of the airplane in gusts to the strains obtained per unit acceleration in a pull-up condition.

The flight investigation was made in the vicinity of Baltimore, Md., in the spring of 1949 in cooperation with the Glenn L. Martin Co. The flights and instrumentation of the airplane were under the direction of the NACA and an NACA contract covered the flight time on the airplane. The U. S. Weather Bureau assisted in the selection of suitable flight days by furnishing daily turbulence forecasts.

APPARATUS AND TESTS

The characteristics of the test airplane, a modern twin-engine transport, are given in table I(a) and a three-view drawing is shown as figure 1. The section moment of inertia and the estimated wing-weight distributions for the conditions of the tests are shown in figure 2. All the fuel load is carried in wing fuel tanks outboard of the engine nacelles.

Resistance-wire strain gages connected as four active gages in a bridge circuit were installed on the wing spars at the spanwise stations shown in figure 3. At each station strain-gage bridges for measuring the strain due to bending moment and shear were mounted on each spar as illustrated by the sketch of a typical installation also shown in figure 3. The strain-gage bridges for measuring bending moment consisted of gages which were mounted on one side of the upper and lower wing-spar flanges with the gages parallel to the flange and were used to obtain strain measurements that would be principally a function of section bending moment. The strain-gage bridges for measuring shear consisted of gages which were mounted on one side of the spar web in an X-arrangement and were used to obtain strain measurements that would be a function of web shear (mounting of the gages on both sides of the spar web was not feasible for these tests). The strain indications were recorded by a multichannel oscillograph. Calibrating loads were applied to the wing at a number of spanwise and chordwise positions and the results showed that the strain indications were a linear function of load for all loading positions. These calibrating loads covered increments of load corresponding to those expected in the flight tests.

Accelerations were measured at a number of spanwise stations as indicated in reference 3, but only the accelerations measured near the elastic axis at station 159, which is the estimated nodal point of the fundamental bending mode, are used in this paper. A standard NACA airspeed-altitude recorder was used to obtain a record of airspeed and altitude. All records were correlated by means of an NACA $\frac{1}{2}$-second chronometric timer.

The tests consisted of flights through clear rough air over a course 50 miles in length. The flight conditions of the three rough-air runs reported herein and designated as runs A, B, and C are given in table I(b) and are the same as those given in reference 3. The different weight conditions were due entirely to variation in wing fuel load. Runs A and B were made at a speed of 250 miles per hour with a difference in weight of approximately 2,000 pounds (1,000 lb per wing) which represents about two-thirds the fuel-weight change experienced in normal transport operations of airplanes of this model. Runs A and C were consecutive runs at 250 and 150 miles per hour, respectively. The slow pull-ups made to obtain data for use as a quasi-static reference were made immediately before and after the rough-air runs at the test speeds of the runs and at higher altitudes where smooth-air conditions were found. Interpolation was used to obtain reference strains at the weight conditions of the flights through gusts.

PRECISION

The instrumentation and the character of the records were such that the individual incremental strain measurements were estimated to be accurate within ±25 microinches per inch, and the individual acceleration increments, within ±0.10g. The strain measurements in pull-ups and the results of the laboratory load calibrations were linear with load within the accuracy of the measurements (it was not known whether web buckling took place and affected the measurements taken on the spar web).

RESULTS

Illustrative time histories of incremental strains and nodal-point accelerations are shown for a pull-up and a portion of a gust record in figures 4(a) and 4(b). As was done in reference 3, the average nodal-point acceleration increments (with effects of higher modes faired if present) are taken to represent the airplane accelerations. For each of runs A, B, and C, peak incremental strains and associated maximum nodal-point acceleration increments for a number of gusts encountered were selected as representative of the data. In figure 5 the means for obtaining the reference strains from the pull-up data is illustrated. The strain per g as evaluated from the pull-up data is given for three wing stations on the front spar for the weight conditions at pull-up. Linear interpolation of these data for the weight conditions of the three runs A, B, and C then gives the desired reference strains as a strain per g. Strains at other values of acceleration follow by direct proportion.

The usual assumption in design - that the loads are quasi-static with no distinction made between the distribution of load due to a gust or due to a maneuver - leads to an implicit assumption that for pull-up and gust conditions the ratio of the incremental stresses developed in the front and rear spars is the same. Inspection of figure 4(b), however, indicates that for flight through gusts the peak web strains do not in general occur at the same time for the front and rear spars. It is apparent therefore that the assumed relation does not hold for the spar-web strains for flights through gusts. To check the validity of the assumption for the spar-flange strains, the incremental strain indications for the front spar were plotted against the indications for the rear spar for each of the spanwise stations for both pull-up and gust conditions as shown in figure 6(a) for run A. Although the web strains for the front and rear spars do not have a unique relation in gusts, a comparison of the ratio of the peak web strains associated with gusts and pull-ups is made in figure 6(b). The peak web strain judged to be associated with a gust was selected for evaluation as, for example, the points marked (a) in figure 4(b) were judged to be associated with the gust acceleration peak marked by (A). The strain relation for pull-ups in figures 6(a) and 6(b) is shown as a single line since it was obtained by interpolation.

The incremental bending strain on the front spar (spar flange) is shown as a function of nodal-point acceleration increment in figure 7 for run A and for the condition applying in pull-ups (from interpolated results as in fig. 5); the corresponding data for web strains are shown in figure 8. With the exception that the data of the low-speed run (C) cover a smaller range of acceleration values, the data for runs B and C were similar to those found for run A and hence are not shown. The dashed lines in figures 7 and 8 represent the estimated mean variation of the gust data; these lines are through the origin and a point which is established as the average absolute value of both the ordinate and abscissa of the data.

The slopes of the lines in figures 7 and 8 are a measure of the strains per g. The ratio of the slope of the line representing the estimated variation for gusts to the slope of the line representing pull-ups can then be considered to be a strain or stress amplification factor. The strains per g for both gust and pull-up conditions and the amplification factors are given in table II; the data therein include both the bending strain and web strain per g for each of the measuring stations on the left wing for runs A, B, and C. The estimated accuracies of these values for runs A and B are given in the following table:

Station	Gusts (percent)	Pull-ups (percent)	Strain amplification factor
Spar flange			
85	±6	±3	±0.1
159	±6	±3	±.1
354	±8	±4	±.1
Spar web			
85	±15	±10	±0.7
159	±15	±10	±.5
354	±8	±5	±.1

The lower acceleration values of run C would lead to somewhat less accuracy than shown in the previous table.

DISCUSSION

Basis of analysis of data.- For flights through gusts, the determination of the stress increment associated with wing flexibility requires knowledge of the stresses developed as well as of what the stresses would be if the wing were considered rigid. Since direct determination of the stresses for the hypothetical rigid-wing condition of course is not feasible, recourse is made to strain-gage measurements in slow pull-ups. These pull-ups are regarded as a simulated rigid-wing condition and the strains for this condition are used as reference values. The strain amplification factor obtained when pull-ups are used as the reference condition, however, not only includes structural dynamic response but other effects as well, such as those due to variations in spanwise gust distributions. The spanwise-gust data of reference 4 indicate that the lateral center of pressure may be inboard of that expected for a uniform gust or that obtained in a pull-up, with the consequence that the strains obtained per g in a pull-up might be slightly higher than those that would be obtained for a rigid wing in gusts. The strain amplification factor referred to the slow pull-up might therefore be somewhat low as compared with calculations.

Analysis of the data on the basis of gust-gradient distance or time to peak acceleration would be desirable for correlation with calculation but was not feasible since the flight data were for continuous rough-air conditions. Unknown effects due to previous gusts as well as effects due to variations in spanwise gust velocity are included in the evaluation of the data and may be expected to introduce scatter. It should also be noted that the amount of scatter should be influenced by unsymmetrical-gust effects.

Bending strains.- Examination of the time histories of the bending-strain increment and nodal-point acceleration increment for slow pull-ups (fig. 4(a)) shows a smooth variation of the histories with no evidence of vibratory effects.

The time histories for a portion of the gust record (fig. 4(b)) show a principal oscillatory motion which can be attributed to the wing fundamental bending mode. A further inspection of the record indicated that these oscillations, with few exceptions, were in phase on the front and rear spars and at corresponding stations on the left and right wings. In some portions of the records significant vibratory strains were found in the absence of any perceptible nodal-point acceleration.

The relationship between the front- and rear-spar bending strains for pull-ups and gust conditions shown in figure 6(a) shows that the same relation holds for both pull-ups and gusts. The structural dynamic-response effects on bending strains at a given spanwise station, therefore, will be the same for the front and rear spar for this airplane.

Although appreciable scatter of individual points in the front-spar bending-strain data for gusts in figure 7 is evident, the trend of the data is roughly linear. The bending strains in gusts shown in this figure are greater, on the average, than in slow pull-ups for the same nodal-point acceleration increment. Consideration of the average bending strain per g for gusts relative to pull-ups (see table II) indicates that the bending strain is, on the average, approximately 20 percent higher for the gust data than for the slow pull-ups for all the test conditions and wing stations considered. When scatter is considered, and if the data for the low values of acceleration are discounted, it would appear that strain amplification factors for individual gusts may range from less than 1.0 to greater than 1.4. Inasmuch as the gust conditions for runs A, B, and C covered by the data in table II would be expected to be approximately the same, it would appear that the structural response in gusts was little affected by either the change in wing weight (1,000 lb per wing) due to fuel load or by a change in forward speed from 150 to 250 miles per hour with a smaller wing-weight change (400 lb per wing).

Shear indications.- Time histories of the strains associated with shear and nodal-point acceleration in slow pull-ups (fig. 4(a)) show that the strains increase positively with nodal-point acceleration except for the front spar at station 85. The recorded strains in pull-ups are quite smooth with no evidence of vibratory strain amplitudes.

The time histories of strain associated with shear for the flights in rough air (see fig. 4(b)) have an entirely different character from those for bending strains because of large vibratory strains, except possibly for station 354. At station 85, the vibratory strains of the front and rear spars are of opposite sign; this relation also held in the pull-ups. There are indications, however, that the vibratory strains of the left wing are out of phase with those of the right wing. In contrast to the data for the pull-up, the strains in the front and rear spars at station 159 appear to be of opposite sign in rough air. At station 354, the front-spar strains (in this case the shear web of the heat de-icer bulkhead) show little or no vibratory strain while the rear-spar web indicates greater effects of vibration. Comparison of the strain vibration frequencies with the fundamental mode frequency indicates that they are about the same. On the basis of these observations, although no reason can be assigned for the particular vibratory character of the records, it appears that nodal-point acceleration would bear no obvious relation to the web-strain values.

In figure 6(b) the maximum front- and rear-spar shear indications judged to be associated with gusts and pull-ups are compared. In contrast to the scatter in the data on bending strains, the shear data show much greater scatter, the scatter being greatest at station 85. The data shown indicate that the relationship of the peak web strains between spars is not the same for pull-ups and gusts.

The peak web strains developed in gusts and pull-ups at given values of nodal-point acceleration are compared in figure 8. The trend of the data for gust conditions is apparently roughly linear, and the strains are greater, on the average, than in slow pull-ups for the same nodal-point acceleration increment. Consideration of the average strain per g associated with shear for gusts relative to pull-ups (see table II) indicates that the amplification factor ranges from a maximum of 3.0 at the inboard stations to a minimum of 1.1 at station 354. No effect of speed or weight is evident from the data.

Considering the lack of any obvious relation between nodal-point acceleration and web strain (see fig. 4(b)), generalization of the web-strain data is not believed warranted.

CONCLUSIONS

The results of strain measurements on a twin-engine transport airplane in rough air and in slow pull-ups indicate that for the airplane tested:

1. The bending strains per unit normal acceleration in gusts were approximately 20 percent higher than those in slow pull-ups for all measuring positions and flight conditions of the tests.

2. The dynamic component of the wing bending strains appeared to be due primarily to excitation of the fundamental wing bending mode.

3. The bending strains in the front and rear spars at each spanwise measuring station showed the same relation to each other in gusts and in slow pull-ups.

4. The data on spar shear strains showed wide scatter, and the estimated shear strain amplifications for gusts relative to pull-ups differed widely with measuring station.

5. The primary component of the web strains for the gust conditions was vibratory and, although it appeared to be at the fundamental wing frequency, was of an antisymmetrical nature with respect to the airplane center line.

6. No significant variation of structural dynamic response with the range of speed and weight conditions covered by the tests was evident from the results.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., May 2, 1951

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2. Jenkins, E. S., and Pancu, C. D. P.: Dynamic Loads on Airplane Structures. Preprint for presentation at the SAE National Aeronautic and Air Transport Meeting. April 13-15, 1948.

3. Shufflebarger, C. C., and Mickleboro, Harry C.: Flight Investigation of the Effect of Transient Wing Response on Measured Accelerations of a Modern Transport Airplane in Rough Air. NACA TN 2150, 1950.

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TABLE I

CHARACTERISTICS AND FLIGHT CONDITIONS OF TEST AIRPLANE

(a) Characteristics

Span, feet	93.3
Mean aerodynamic chord, feet	10.1
Wing area, square feet	870
Aspect ratio	10
Center-of-gravity position in tests, percent M.A.C.	22
Fundamental wing frequency, (Glenn L. Martin ground-vibration tests, W = 25,600 lb), cycles per second	3.8
Estimated fundamental wing frequency in flight for test conditions, cycles per second	3.7

(b) Flight conditions for rough-air runs

Run	Average gross weight (lb)	Speed (mph)	Altitude (ft)
A	33,650	250	3,000 to 4,000
B	31,550	250	3,000 to 4,000
C	32,850	150	3,000 to 4,000

TABLE II

STRAIN INDICATION PER g FOR GUSTS AND PULL-UPS AND STRAIN AMPLIFICATION FOR GUSTS RELATIVE TO PULL-UPS

Station	Strain indication per g (microin./in./g)						Strain amplification factor (gust/pull-up)		
	Gusts			Pull-ups					
	Run A	Run B	Run C	Run A	Run B	Run C	Run A	Run B	Run C
(a) Spar flange (bending strains)									
Front spar									
85	583	595	561	455	475	462	1.28	1.24	1.21
159	673	672	675	555	581	565	1.21	1.16	1.19
354	292	296	302	257	248	252	1.14	1.19	1.20
Rear spar									
85	555	580	530	448	480	458	1.24	1.21	1.16
159	602	617	585	500	525	510	1.20	1.18	1.15
354	351	366	371	296	293	296	1.19	1.25	1.25
(b) Spar web (shear strains)									
Front spar									
85	236	229	224	78	82	81	3.0	2.8	2.8
159	260	267	211	107	107	107	2.4	2.5	2.0
354	282	270	272	250	238	246	1.1	1.1	1.1
Rear spar									
85	149	158	171	98	107	102	1.5	1.5	1.7
159	162	175	140	82	92	85	2.0	1.9	1.6
354	415	464	403	349	340	345	1.2	1.4	1.2

NACA

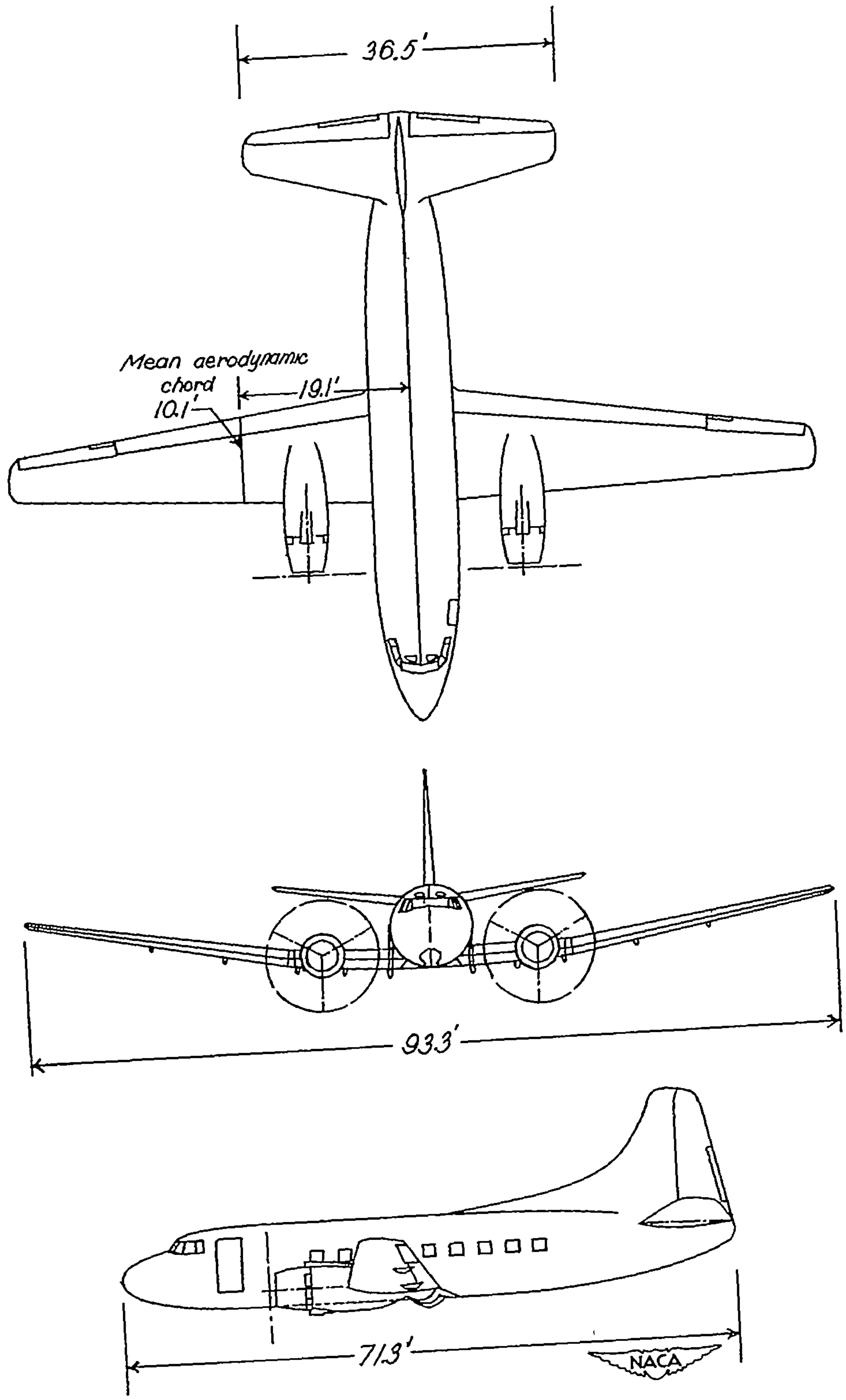


Figure 1.- Three-view drawing of test airplane.

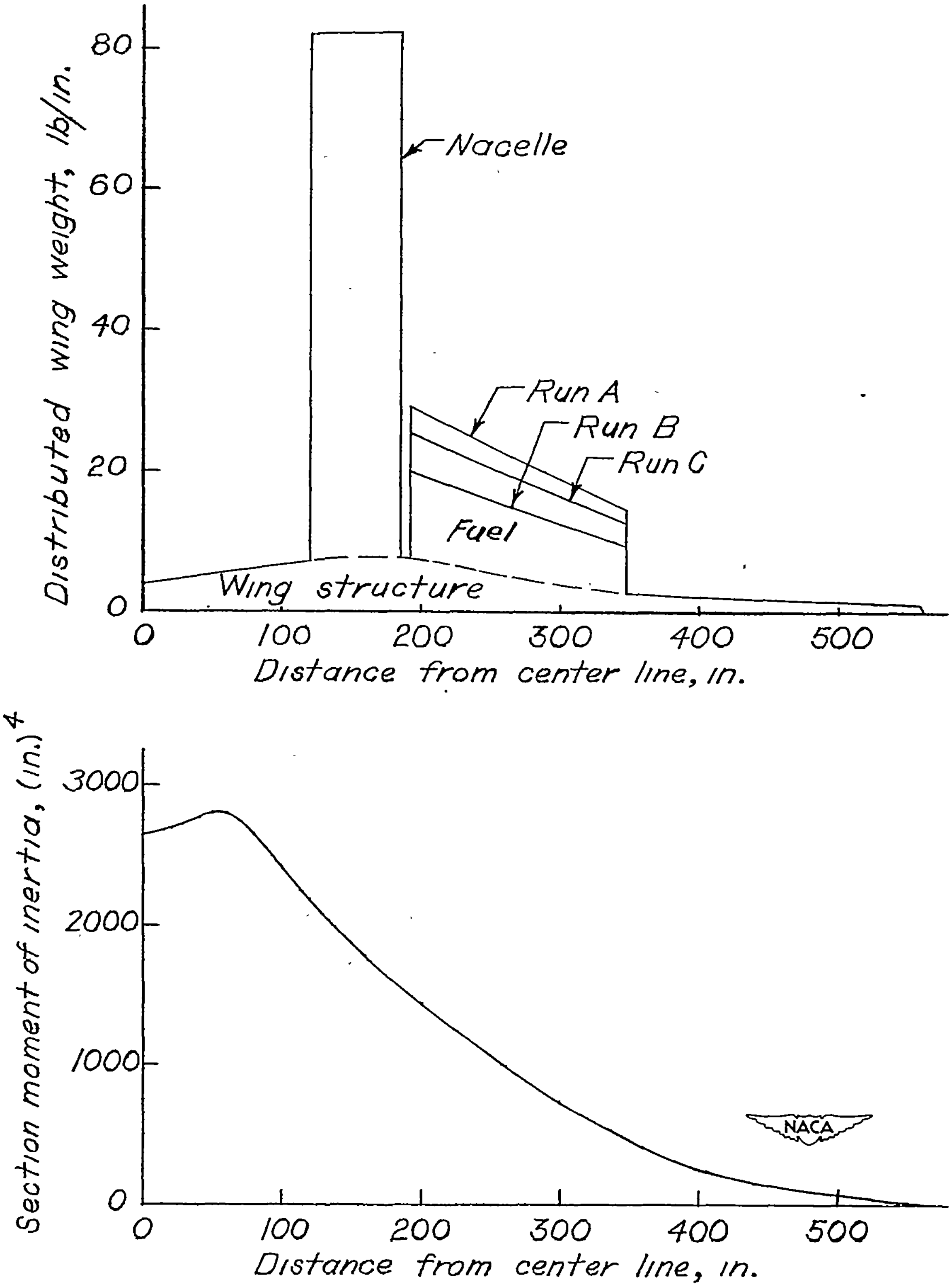


Figure 2.- Section moment of inertia and estimated wing-weight distributions.

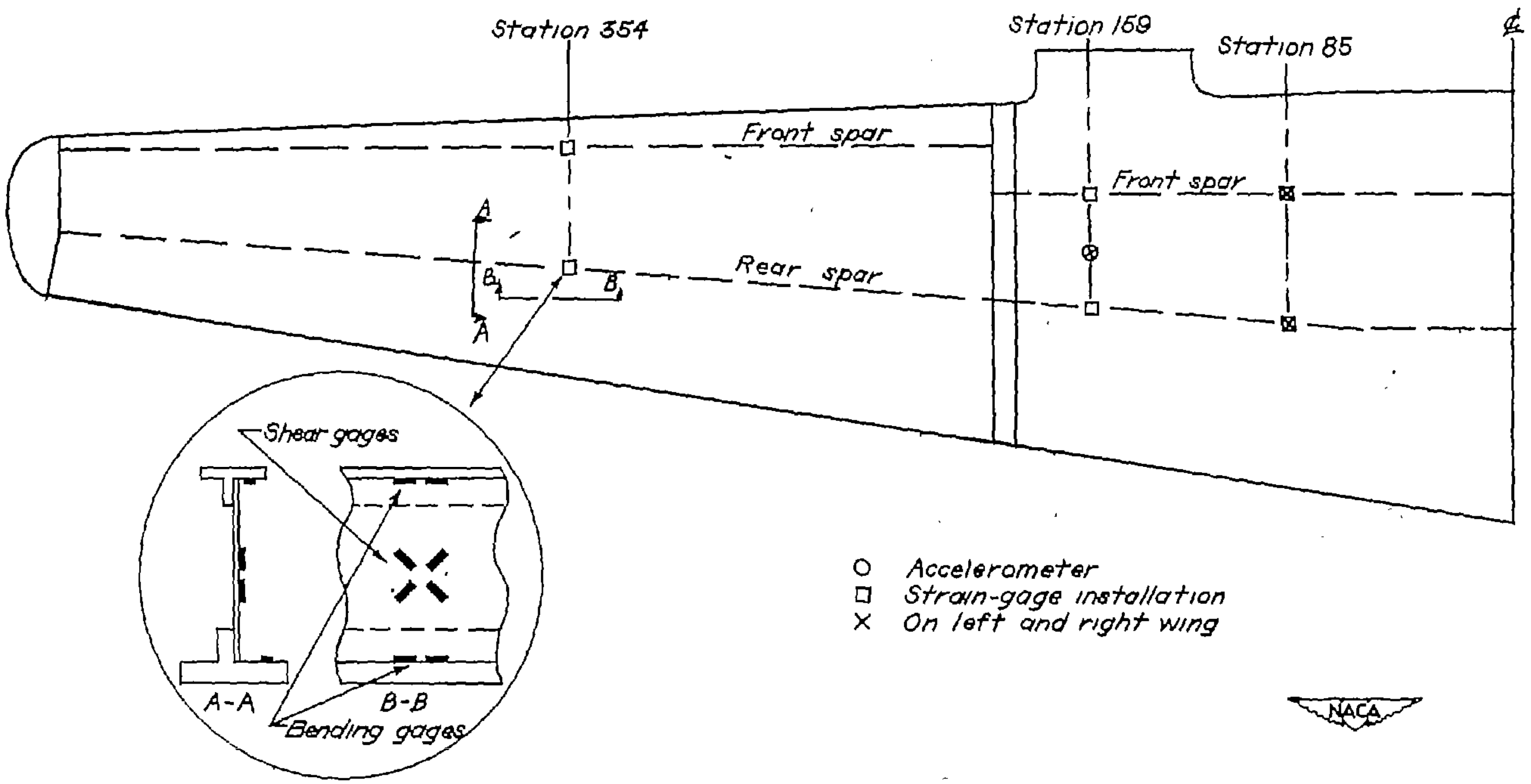
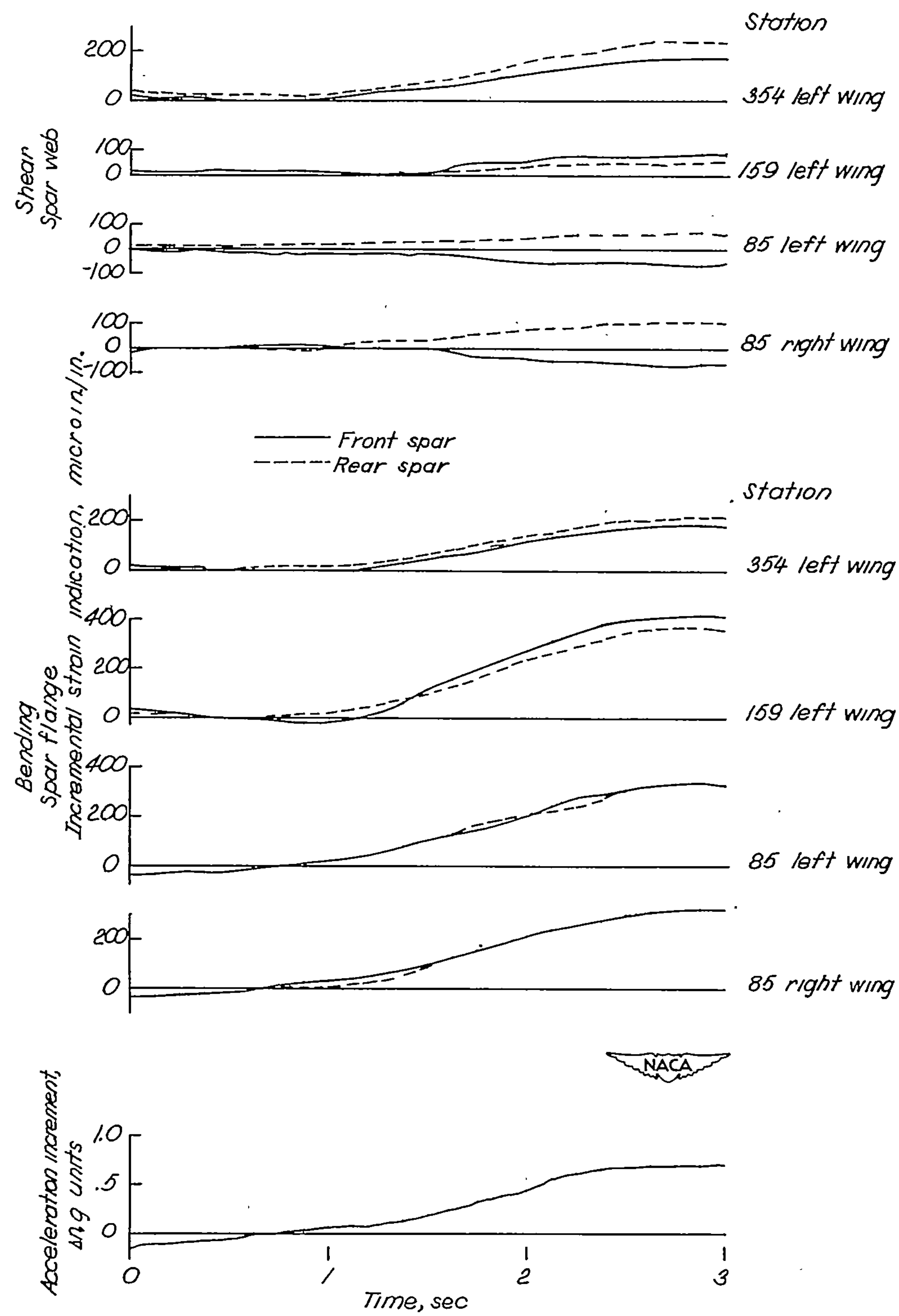
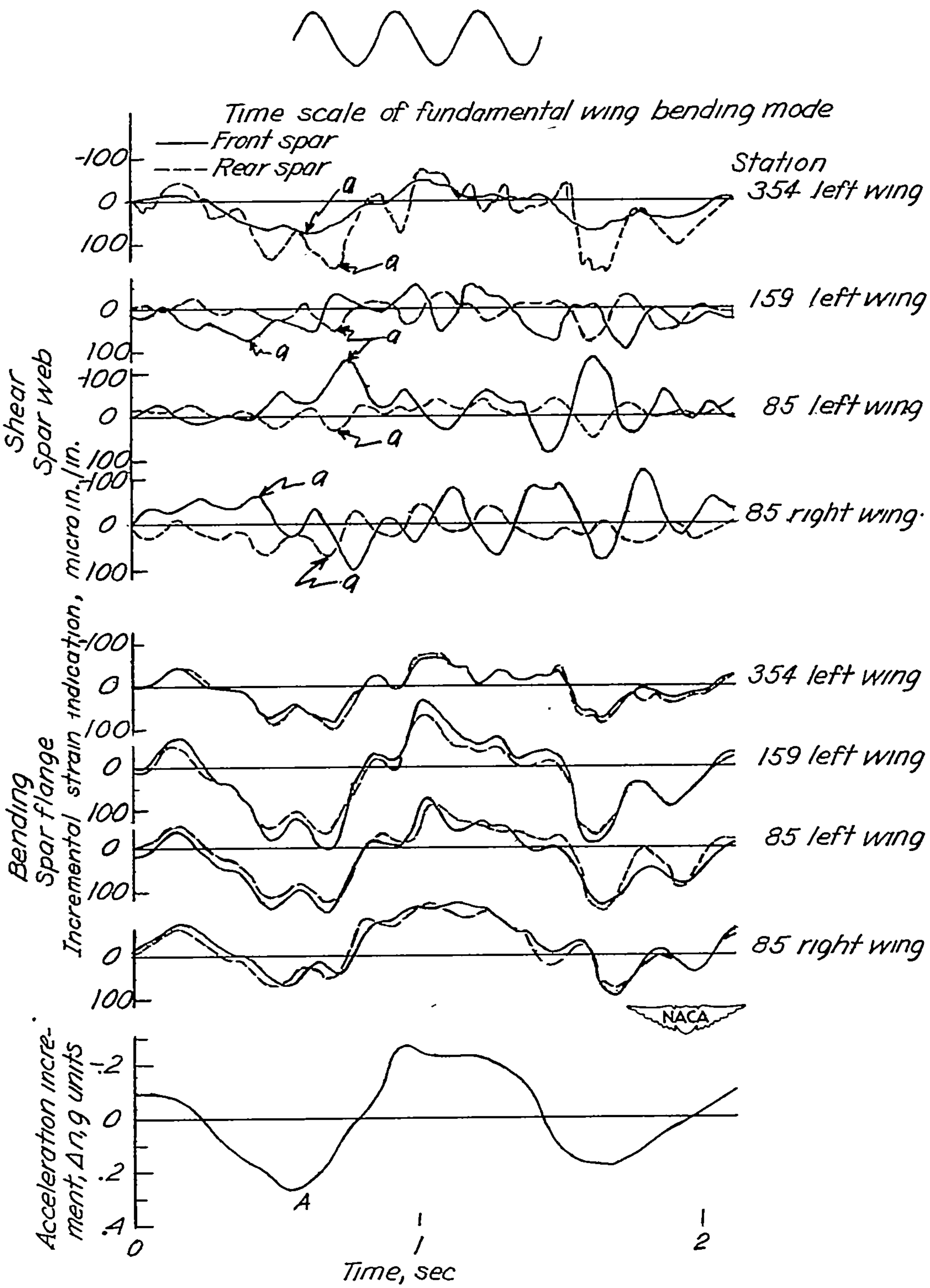


Figure 3.- Location of accelerometer and strain-gage installations in left wing of test airplane.



(a) Pull-up.

Figure 4.- Time histories of incremental wing strain indication and nodal-point acceleration.



(b) Portion of gust record.

Figure 4.- Concluded.

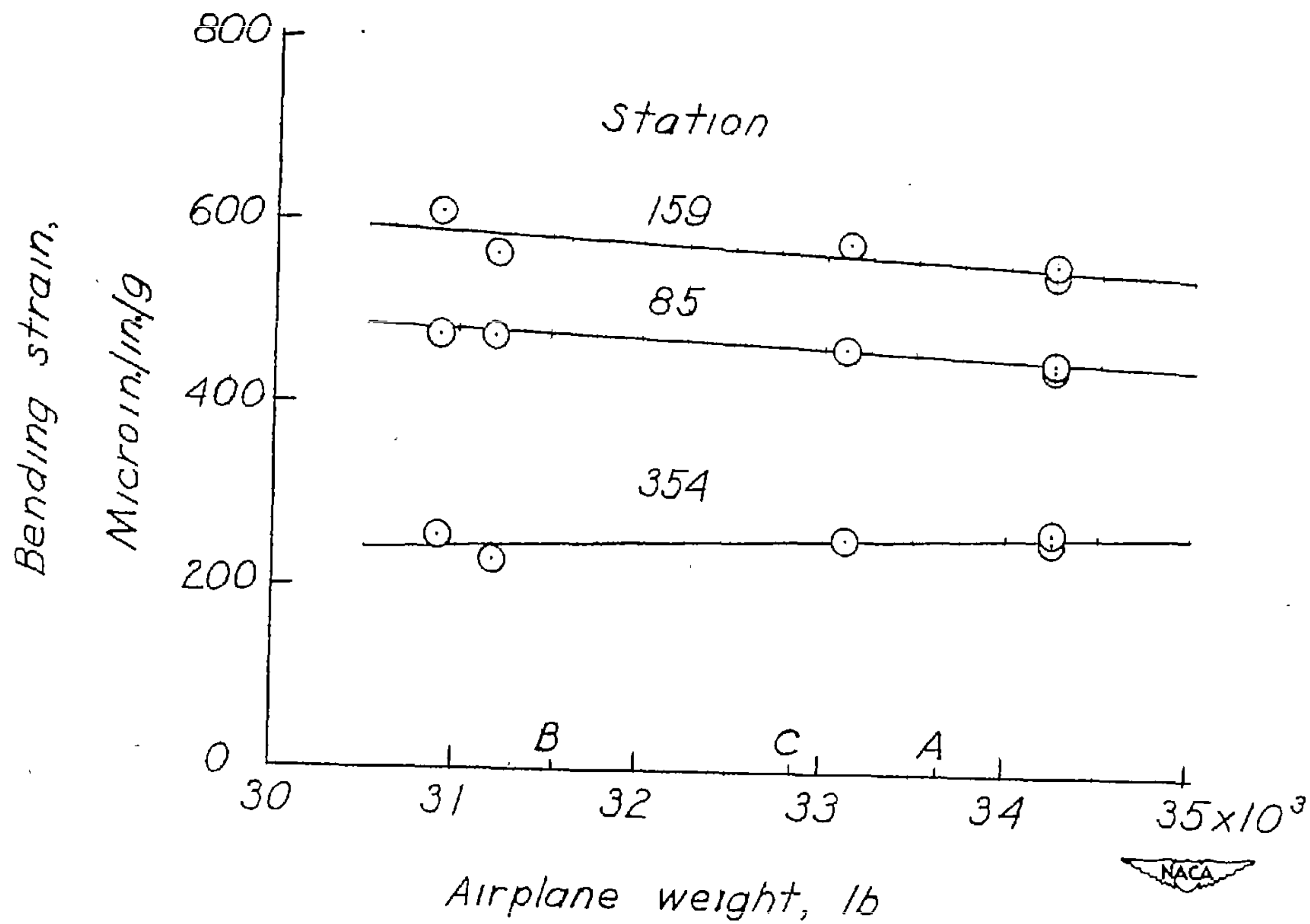
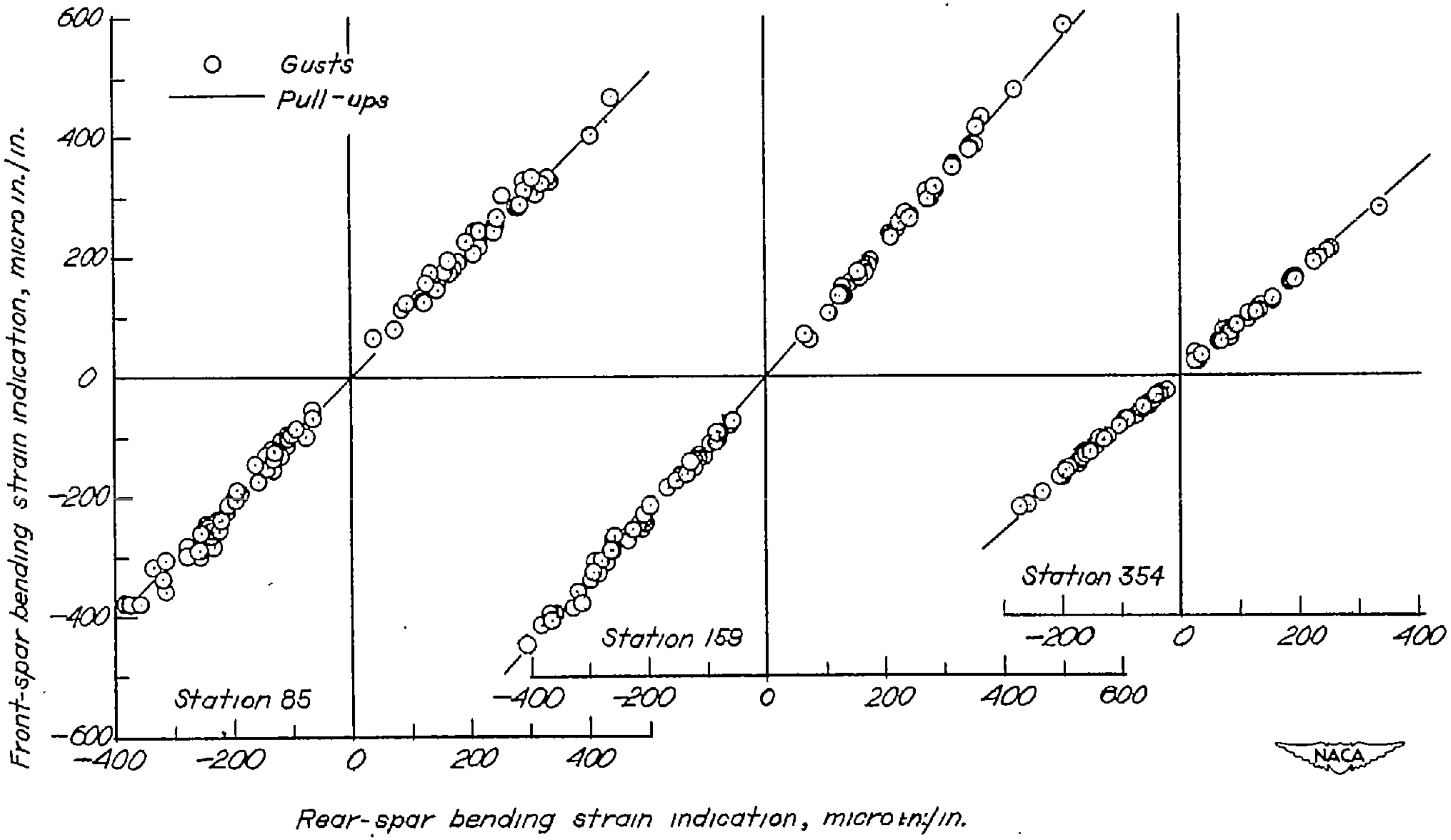
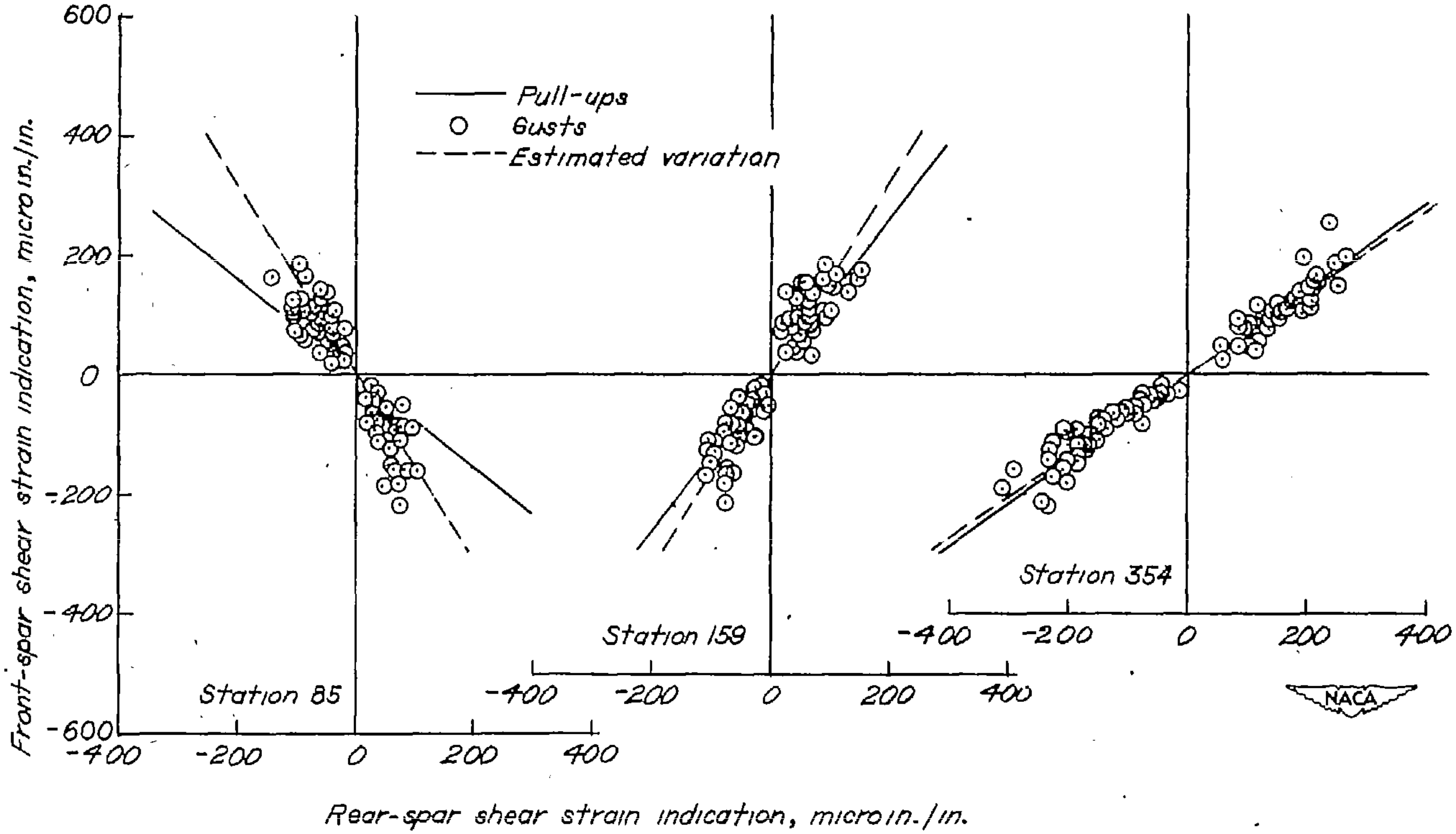


Figure 5.- Variation of bending strains with airplane weight for pull-up conditions. Front spar; left wing.



(a) Flange bending indications.

Figure 6.- Strain indications on front spar as a function of strain indications on rear spar for gust and pull-up conditions at each spanwise station on left wing. Run A.



(b) Web shear indications.

Figure 6.- Concluded.

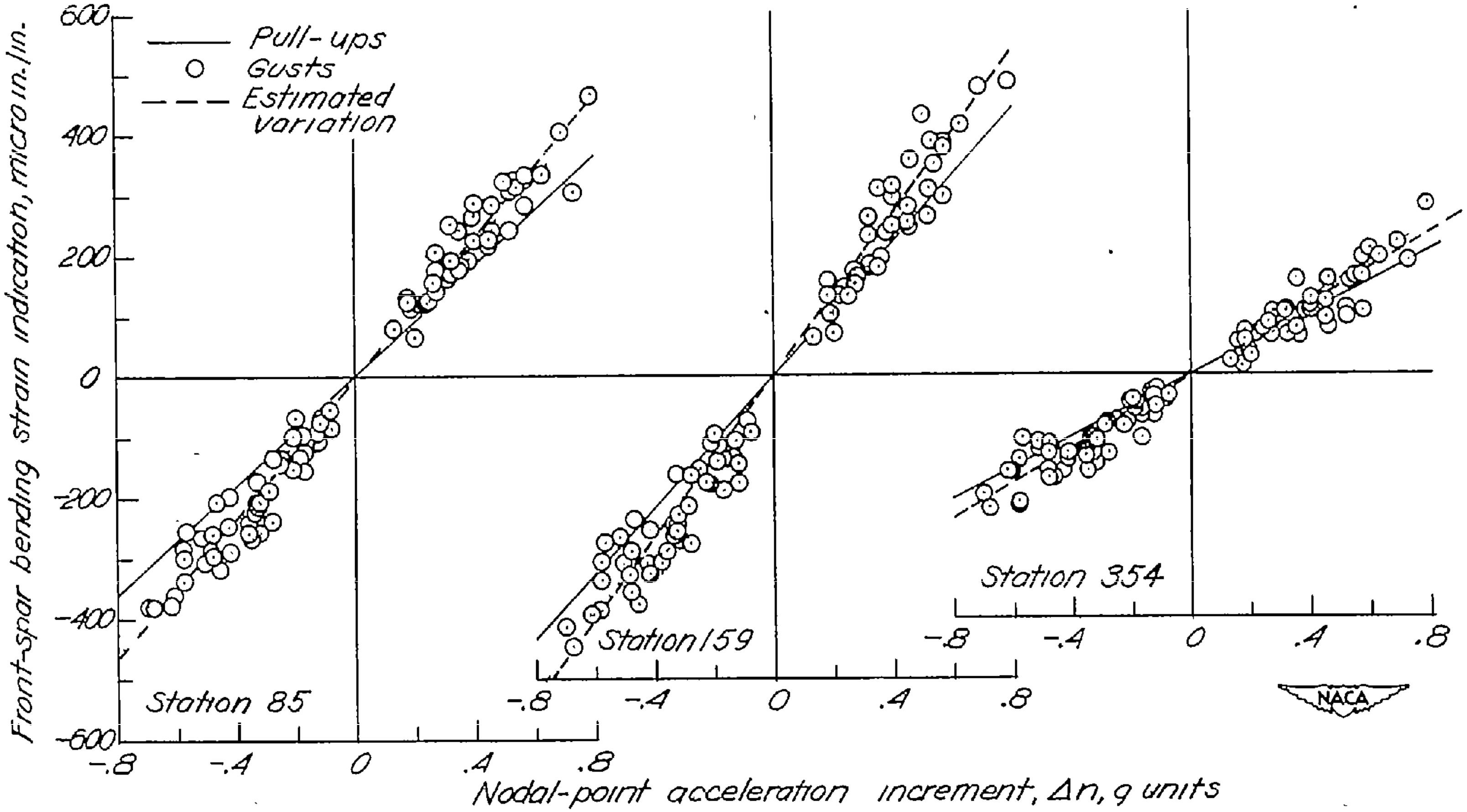


Figure 7.- Incremental strain indications on spar flange as a function of nodal-point acceleration increment for front spar, left wing, for gust and pull-up conditions. Run A.

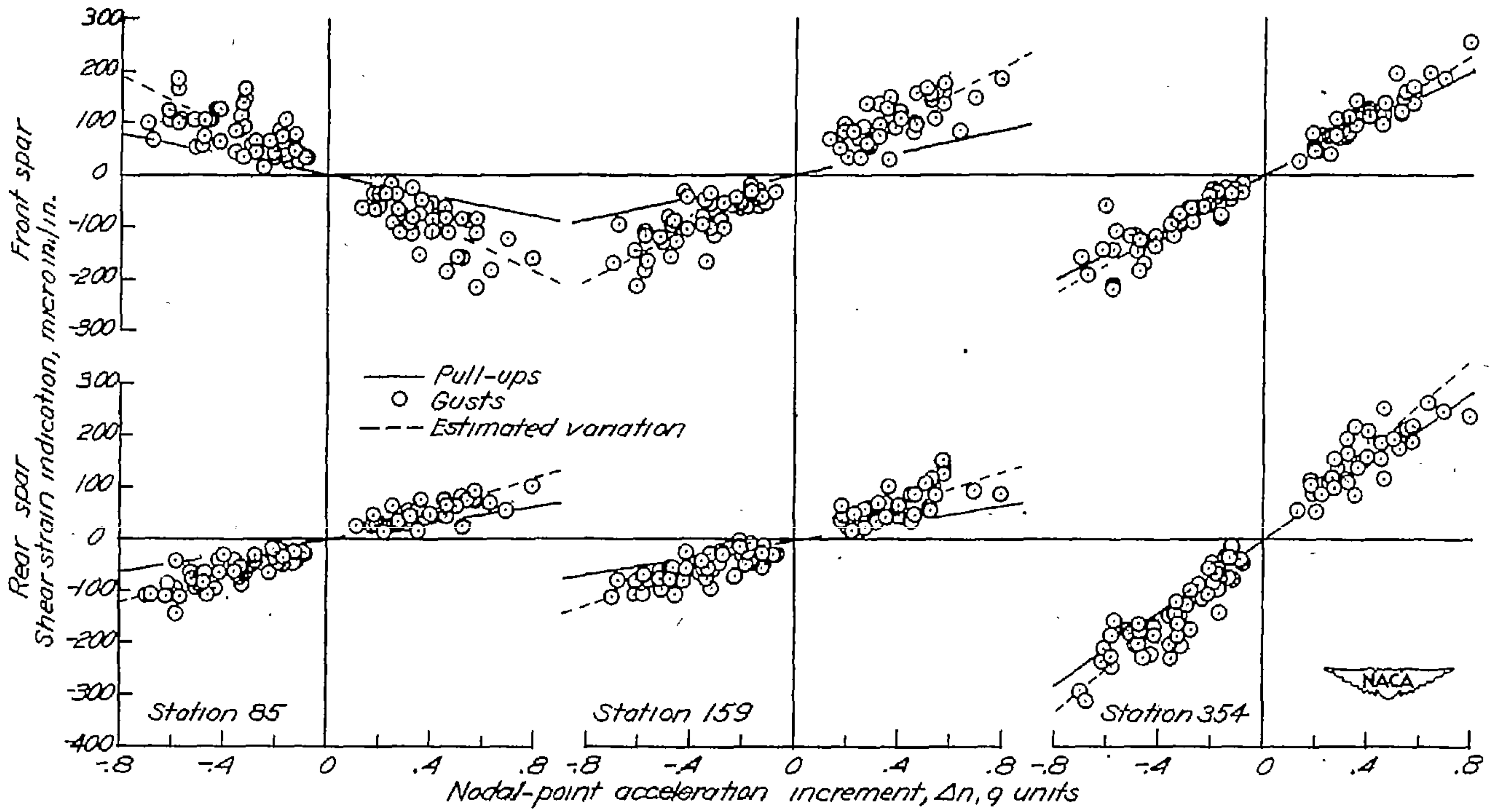


Figure 8.- Incremental strain indications on spar web of left wing as a function of nodal-point acceleration increment for gust and pull-up conditions. Run A.